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Preparation of Truck Version PHS Variable Dilution Sampling System

Southwest Research Inst, San Antonio, Tex

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SPECIAL REPORT
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I. INTRODUCTION

One objective of the work efforts under Modification No. 4 to Contract PH 86-67-73 "A Study of Truck Emissions Powered by Spark Ignited Engines" was to prepare truck version of the Public Health Service variable dilution exhaust sampling system. This report covers the preparation of this sampling system as well as some limited results using this method as compared with proportional sampling system.

In June 1967, the details of the initial prototype variable dilution sampling method were disclosed in an Air Pollution Control Association paper by Messrs. Broering, Werner, and Rose, Reference 1. As mentioned in the Introduction of this paper:

> "With the advent of national standards for the control of automotive exhaust emissions, the need for simple and accurate sampling and analytical techniques for automotive exhaust emission testing has become more critical. Present continuous measurement techniques, provided for in both the Federal and the California Automotive Exhaust Emission Standards, require elaborate sampling and instrumentation. Moreover, the emission levels indicated by the continuous technique used in the present standards are measured on a concentration basis and adjusted by weighted mean air flows, which gives only an indirect general measure of the air pollution potential of a given vehicle. In contrast, when mass-emission levels are used as emission criteria, direct assessment of the air pollution potential of a vehicle can be made."

The principle of operation of the system is the collection and simultaneous dilution of the total exhaust volume from the vehicle with a variable volume of dilution air such that the total mass flow rate of exhaust gas plus diluent air is constant for a given unit of vehicle operation. Consequent measurement of emissions concentration in the exhaust-diluent air mixture would then provide a direct measurement of the mass of contaminants emitted per unit operation of the vehicle. The prototype system consisted of an air to exhaust heat exchanger, a large positive displacement rotary pump as the prime mover to handle the total exhaust from the vehicle, regardless of operating condition, plus substantial diluent air via a large pipe located around the vehicle exhaust pipe. A small sample of the total exhaust of the vehicle, plus the diluent air, after passing through the heat exhanger, was then obtained prior to its entry into the large rotary pump and deposited in a Tedlar* sample bag. This sample was taken at a constant rate through a small rotary positive displacement pump. For mass emission measurements, the samples deposited in the

*E. I. duPont de Nemours, Inc., and Co.

Tedlar bag were then available for analysis on an integrated, overall, basis. For continuous mode mass emission measurements, samples are available after the sample pump for analysis by standard exhaust measurement techniques.

The variable dilution sampler was shown, in Reference 1, to correlate well with samples obtained via the proportional method for the automobiles studied. By obtaining equally satisfactory results with the variable dilution system, use of the proportional sampler may be minimized. The proportional sampling system, however, remains a powerful tool in the development of dynamometer cycles, acquisition of exhaust samples during operation on closed road courses, and other related sampling requirements.

The prototype PHS variable dilution sampling system was specifically designed to accommodate passenger cars and vehicles which use passenger car type and size power plants. In order to obtain baseline data as described in Modification No. 1 to Contract PH 86-67-72, a truck version of the prototype unit was required capable of handling the exhaust from trucks above 10,000-lb GVW.

II. DISCUSSION OF TRUCK VERSION OF VARIABLE DILUTION SAMPLER

The objective of this portion of the program was to prepare a version of the Public Health Service variable dilution sampling system for use with gasoline powered trucks above 10,000-lb GVW. The approach was to retain the design criteria used in preparation of the prototype, summarized as follows:

(1) Provide for the rapid and accurate determination of the quality and quantity of exhaust being emitted.

(2) Ensure chemical stability.

(3) Permit determination of the mass of contaminants emitted both overall and during individual modes.

To assist in emulating the prototype, duplicate copies of the original purchase orders were furnished by the Technical Officer. In the adaptation of the automotive prototype to truck exhaust, these originally specified items of equipment, hardware, etc., were obtained except where design changes were warranted. The following subsections cover the adaptation and preparation by SwRI of the truck version of this new sampling method.

A. Design Changes

The most important design change required to adapt the automotive prototype for operation with gasoline trucks was to increase the exhaust gas handling and dilution capability of the system. This was necessary to accommodate the two- to threefold increase in exhaust from the larger displacement truck size engines, which are operated on a duty cycle different from automobiles. Because the sampling system is employed with vehicles which undergo a variety of carburetor throttle plate settings and engine speeds, which result in a wide variety of exhaust gas flow rates, only overall average design conditions and estimates of flow could be used to estimate the magnitude of redesign necessary. Using approximate figures, it was reported that the variable dilution system was intended to result in a minimum of 4 parts of diluent air for every part of exhaust flow on an overall average basis, resulting in a dilution level of about 5:1. Based on an average exhaust gas flow rate for the majority of automotive vehicles under present and under development cycles, this meant that an overall gas flow rate including the exhaust and diluent air of approximately 300 cubic feet per minute (cfm) would be necessary for the automotive variable dilution sampler.

Considering the increased exhaust gas flow expected with the larger displacement truck engines operated under a higher airflow duty cycle, a maximum design estimate of approximately three times that employed with the prototype automotive unit was adopted as the upper limit. This meant that the system should be capable of handling about 900 to 1000 cfm of exhaust plus diluent in order to maintain the approximate 3:1 minimum dilution level desired. During this analysis of expected engine exhaust flow rates for the wide variety of truck engine sizes, it was determined that a lower gas handling capability should also be available, if possible. This condition, midway between the automotive and large truck applications, should be able to accommodate engine airflows in the vicinity of 200 cfm, such as the exhaust flow rate from a truck near 10,000-lb GVW weight size. This additional design criterion resulted in maintaining the 3:1 dilution of an overall flow of exhaust plus diluent of about 600 to 650 cfm. Other design changes were minor in nature and basically involved improved instrumentation and packaging of the system to require less floor space, etc.

To handle the increased flow of diluent and exhaust, a Roots-Connersville Model RAI 615 horizontal inlet and outlet rotary blower was selected. For purposes of this report, this blower will be known as the "system blower." A two-speed, three-phase, 208-volt, 60-cycle, constant torque, AC electric motor capable of up to 7.5 hp at 1700 rpm and up to 5 hp at 1150 rpm was selected to direct drive the RAI 615 blower through a suitable Dodge Paraflex coupling. This resulted in the approximate 600 to 650 cfm at the low motor speed of 1150 and 900 to 950 cfm at the high motor speed of 1700 rpm. To maintain both the low and high motor speed, which is essential to the flow parameter of constant volume of gas flow, a three-phase, Y-connected 10.66-kva powerstat was added to maintain constant line voltage. This powerstat resulted in speed stabilization and adjustment by means of input voltage and proved to be an important new feature.

Next, the prototype PHS all stainless steel heat exchanger was studied for its diluted exhaust handling capability and its heat transfer capacity. This proved to be one of the most difficult design portions of the preparation of the truck version in that good basic data regarding peak flow rates and exhaust temperatures were not available, and it was difficult to determine the heat transfer efficiency of the existing prototype unit during cyclic flow and temperature conditions. Because of these limitations and the importance of this item, the heat transfer calculations and the flow capability of the original design were carefully reexamined. It is determined that the majority of the heat contained in the exhaust gas was transferred to the entrained diluent shortly after the exhaust plus diluent entered the flexible stainless pipe but prior to the heat exhanger. The majority of the heat exchange would be through this exhaust to air transfer medium, resulting in an overall higher than ambient diluted

exhaust temperature. It was then necessary to analyse the potential of the heat exhanger in reducing the peaks that would normally be expected during acceleration and maximum power conditions which produce maximum flows of exhaust at their maximum temperature. The prototype shell and tube type heat exchanger appeared to have ample heat exchange capacity to smooth out most of the peaks that might be expected during operation. Some design changes were made, however, to permit the threefold increase in diluted exhaust flow without greatly affecting the pressure drop across the heat exchanger. To do this, it was decided to maintain the heat exchanger shell and tube design essentially as originally designed but to increase the diameter of the eighty-one tubes from 3/4- to 1-in. OD. The 304 stainless steel, 20-gauge tubes were retained. The location of the tubes in the tube sheets and the length of the tubes remained the same so that the overall size of the heat exchanger was unchanged. Even though the tubes were enlarged, the residence time of the exhaust in the heat exchanger was decreased. This improved the response of the system but decreased the heat transfer efficiency. To increase the ability of the heat exchanger to reduce the temperature of the diluted exhaust gas, it was determined that a substantially larger cooling air blower be employed. Heat transfer through stainless steel is poor compared to other heat exchanger materials, justifying this decision. A Chicago airfoil fan series "S-Q" with 3-hp, three-phase, 3450-rpm, AC motor was used to belt drive the cooling air through the shell of the exchanger. The mounting flange was redesigned to permit mounting of the larger fan directly on top of the heat exchanger. Additional exit area at the opposite end of the shell was provided to permit the cooling air to escape after passing over the tubes.

The next design change involved driving the small, nickel plated XA-22 series Roots-Connersville rotary sample pump by means of a separate 1/2-hp, three-phase, 1150-rpm, 208-volt motor. This item will be referred to as the "sample pump." A cog belt drive system was used to reduce the motor speed to 760 rpm and obtain the near 4-cfm sample flow rate desired. A number of minor features were incorporated to instrument and control the operation of the sampling system. Bare element, 30-gauge iron-constantan type J thermocouples were installed in six locations, and a suitable, single-point strip chart recorder, Leeds and Northrup Speedomax W was selected for monitoring various temperatures. A Thermo-Electric selector switch was also provided to permit monitoring of any one of six temperatures, continuously. Another design feature was to permit measurement of both the system blower and sample pump speed, rpm, using small sixty-tooth gears and magnetic transducers. To count the number of revolutions that the sample pump turns during an operating cycle, and thereby measure the total flow of sampled exhaust not deposited in the large bag, a modified, sixty-tooth gear was employed. Although not a part of the sampling system, an available Swi Hewlitt-Packard Model 521 electronic counter has been used with suc is to

measure blower and pump rpm and total sample pump revolutions. By means of a microswitch mounted on the three way sample valve, revolution counting begins simultaneously with movement of the valve to the sample position and terminates when the sample period and sample valve are in the vent position. Provision was also made for continuous sampling with suitable Swagelock, quick disconnect, stainless steel, double end type connectors.

Because of the two-speed nature and different dilute exhaust flows at the point of exhaust sampling, provision was made to remove and replace the isokinetic probe sized for the high speed, high flow rate system with a smaller sized unit to permit isokinetic sampling at the low speed configuration. The entire sampling system was rearranged to result in a more compact package and consume less floor space than the prototype. In addition, provision was made for a larger sample bag of 4 ft wide × 9 ft high instead of the somewhat smaller bag used with the automotive system. However, in rearranging the system, the objective was to minimize dead space and maximize response while obtaining a representative isokinetically sampled flow. For this reason, the sample probe was located at the end of a fairly long straight section. Instruments, motor controls, and other items in need of attention and operation were placed with the purpose of being functional, as well as attractive and easy to reach.

The final design change made to this sampling system became apparent after the unit was placed into operation with trucks and samples were obtained. The approximate 950 cfm of diluted exhaust were found to affect the exhaust emissions and engine operation, when the 6-in. flexible stainless steel exhaust sampling pipe was placed over the exhaust pipe of certain vehicles. Location of the 6-in. flexible pipe over the exhaust pipe resulted in a partial vacuum in the exhaust system. Up to 4 in. of water vacuum were measured via a tap located between the muffler and engine during idle and closed throttle deceleration. The design change recommended was to attach a cone to the entrance of the stainless steel flexible pipe to increase the inlet area of the exhaust pipe from 18.8 in^2 (6 in. diameter) to 113 in^2 (12-in. diameter), and thereby reduce the high entrance velocity from 7280 to 1210 ft per min during high speed operation. This design modification effectively eliminated the partial vacuum in the vehicle exhaust system attributable to the high inlet air rate into the exhaust pipe and sampling system. Additional details regarding this modification will be described in a later portion of this report.

B. Description

Shown in Figure 1 is a schematic similar to Figure 1 of Reference 1 of the truck version of the PHS variable dilution sampling system. The collecting duct which is a 15 ft length of 6-in. stainless steel flexible pipe

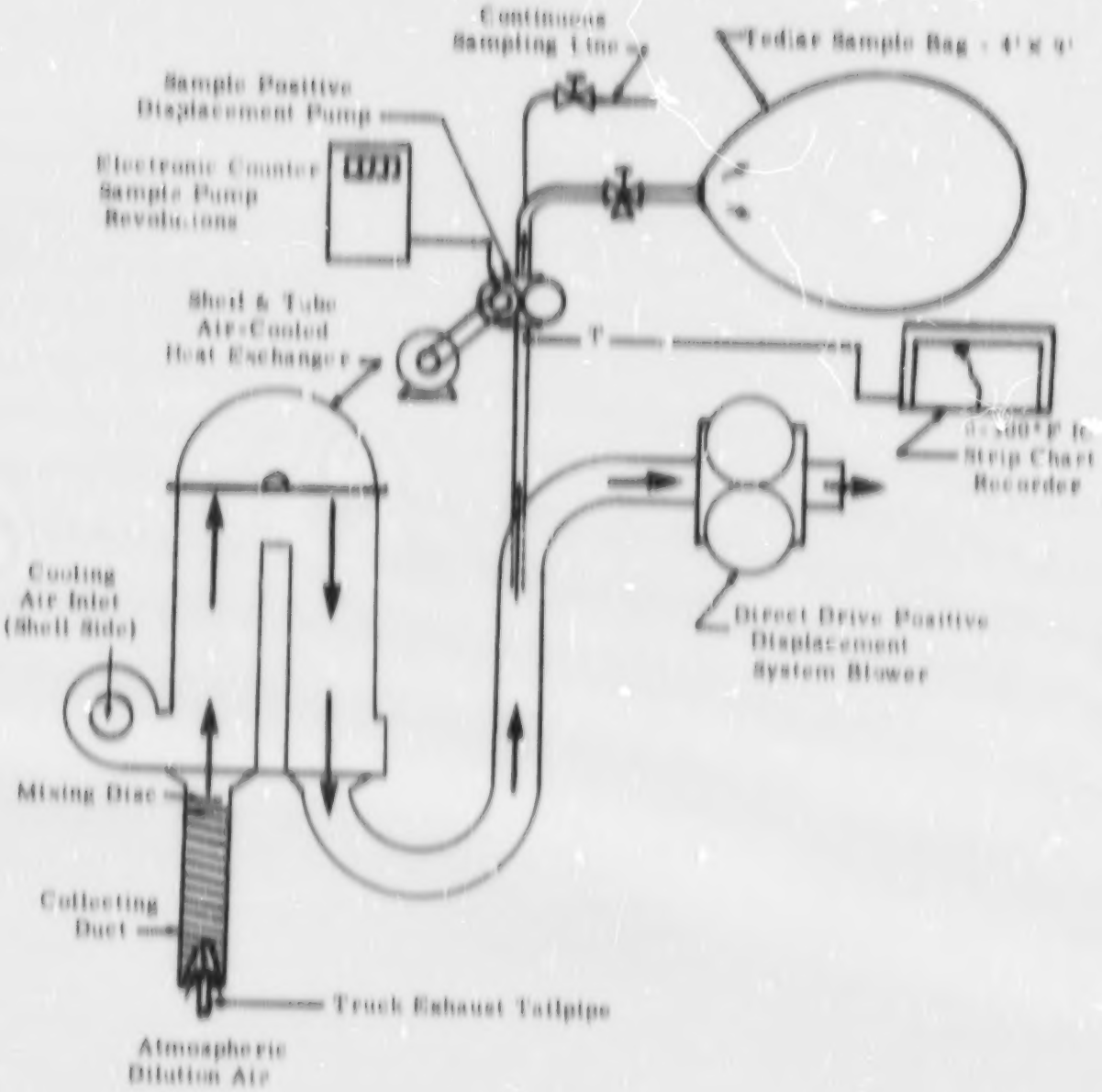

FIGURE 1. VARIABLE DILUTION SAMPLING SYSTEM SCHEMATIC

is placed over the truck exhaust tailpipe such that the exhaust and diluent air is simultaneously obtained. This combined flow then passes a mixing disc to permit additional mixing of the exhaust and diluent into an air-to-exhaust heat exchanger of the shell and tube type. The diluted exhaust then is drawn into the direct drive system blower and then into a long flexible exhaust hose for removal from the laboratory. A 4-cfm sample of the diluted, cooled, and well-mixed exhaust is obtained prior to the inlet of the large rotary pump via an isokinetic sample probe located in the center of the 6-in. stainless steel pipe connecting the heat exhanger with the system blower. This sample of diluted exhaust is obtained via the sample pump and deposited in the Tedlar sample bag shown. A suitable electronic counter and strip chart temperature recorder are employed to monitor the sample flow and temperature. Provision is made for continuous sampling when desired at the outlet of the small sample pump. A large cooling air fan is mounted on the heat exchanger.

To further describe the truck version, Figures 2 through 9, photos taken of the completed system are provided. From Figure 2, designated the front view, it may be seen that the exhaust gas and diluent air mixture enters the sampler cart on the left side via a 6-in. diameter stainless steel flexible pipe which contains a disc to promote turbulent mixing at the entrance to the heat exchanger. The rear view of the sampler cart, shown in Figure 3, more clearly depicts the line of flow of the gaseous mixture. As the gas enters the sampler cart from the 6-in. flexible pipe, it is pulled through the 1-in. OD 20 gauge stainless steel tubes in the lower half of the heat exhanger, and then routed via the "U" bend to the top half of the unit. The tubes of the heat exchanger can be seen in the lower right corner of the exchanger. This is the exit point of the coolant air. Mounted above the heat exchanger, shown in both Figures 2 and 3, is the cooling fan used to force air through the shell of the heat exchanger. As shown in Figure 3, the diluted and cooled exhaust exits the heat exchanger at the top half of the "U" shaped heat exchanger. The diluted exhaust, Figure 4, the left-end view, travels to the inlet of the system blower via 6-in. schedule 10 type 304 stainless steel pipe. The diluted exhaust then exits the system blower through a 25-ft long, 8-in. diameter flexible hose shown in Figure 4. This black hose is used to remove the diluted exhaust from the test cell and normally terminates outdoors.

The two-speed drive motor, direct connected to the system blower, is shown in Figure 5, a close-up front view of the sampling machine. Additional features of the sampler such as the three-phase powerstat, sixty-tooth gear used to measure the system blower speed, and the electrical system controls, motor starters, etc., may be seen. Figure 6 shows additional details as seen by looking down from the top of the machine. Of importance in this and Figure 7 is the location of the sample probe and its relationship to the straight piece of 6-in. stainless steel pipe interconnecting the outlet of the heat exchanger and the inlet of the system blower. A

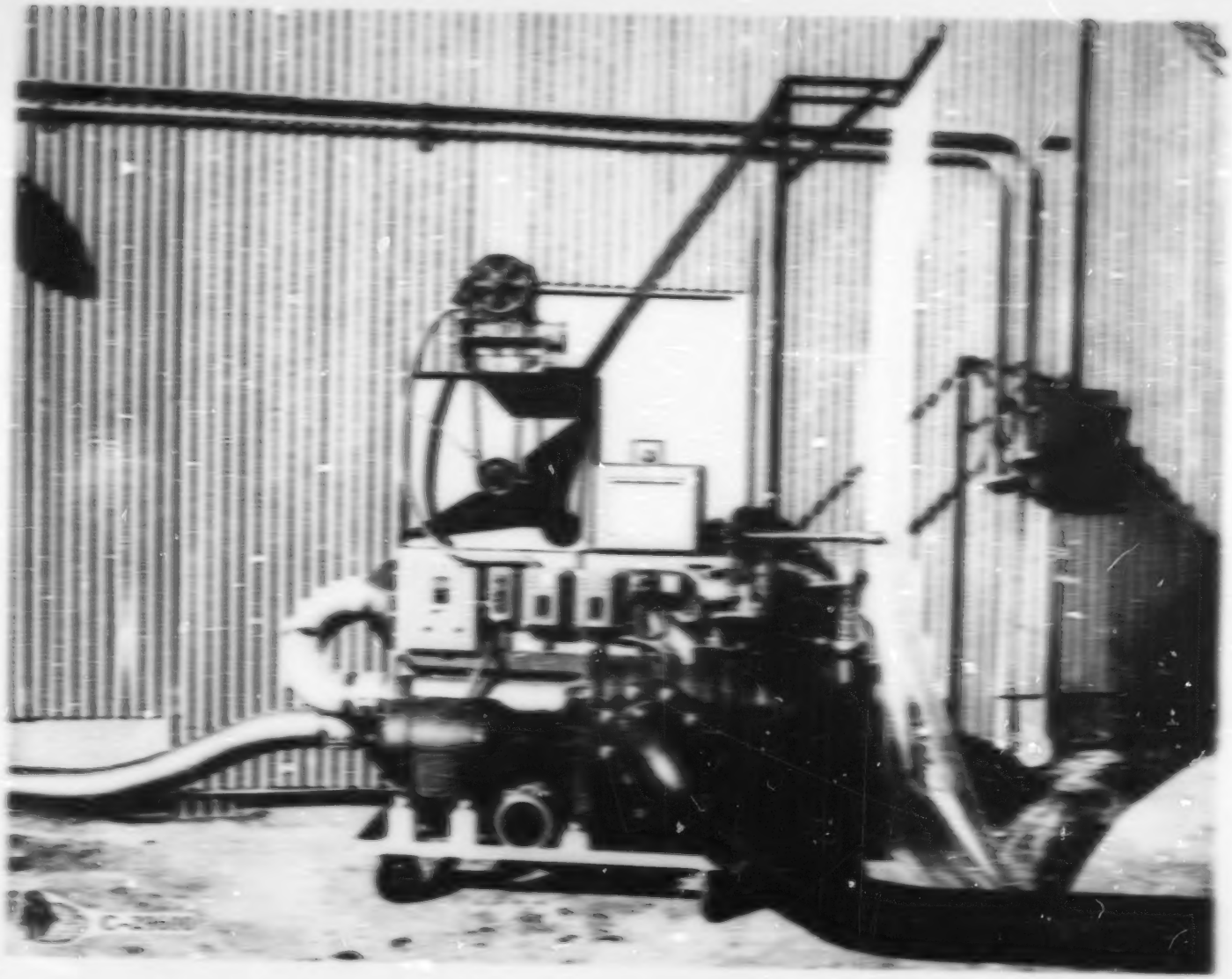

FIGURE 2. VARIABLE DILUTION SAMPLER - FRONT VIEW

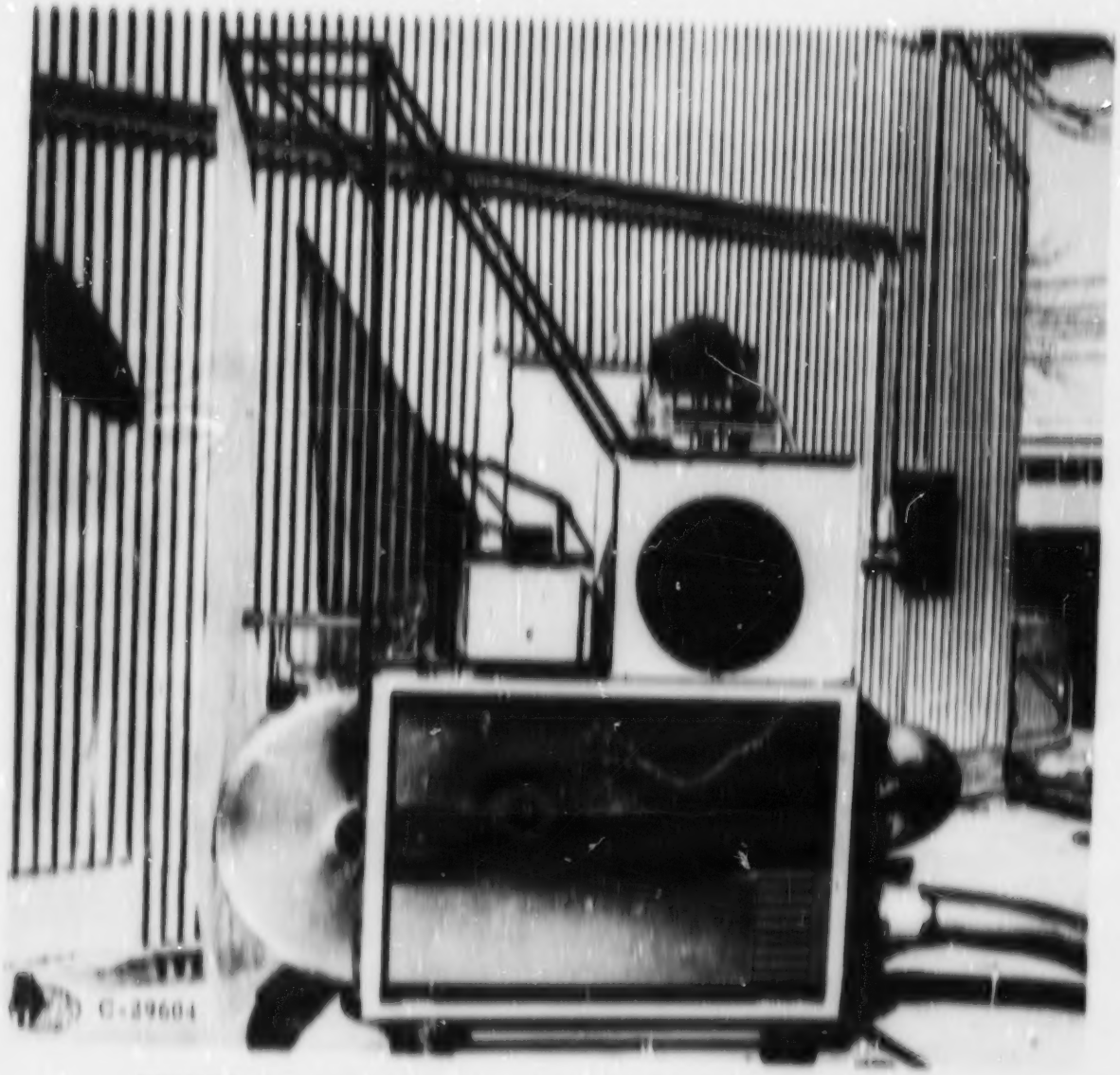

FIGURE 1. VARIABLE DILUTION SAMPLER - REAR VIEW

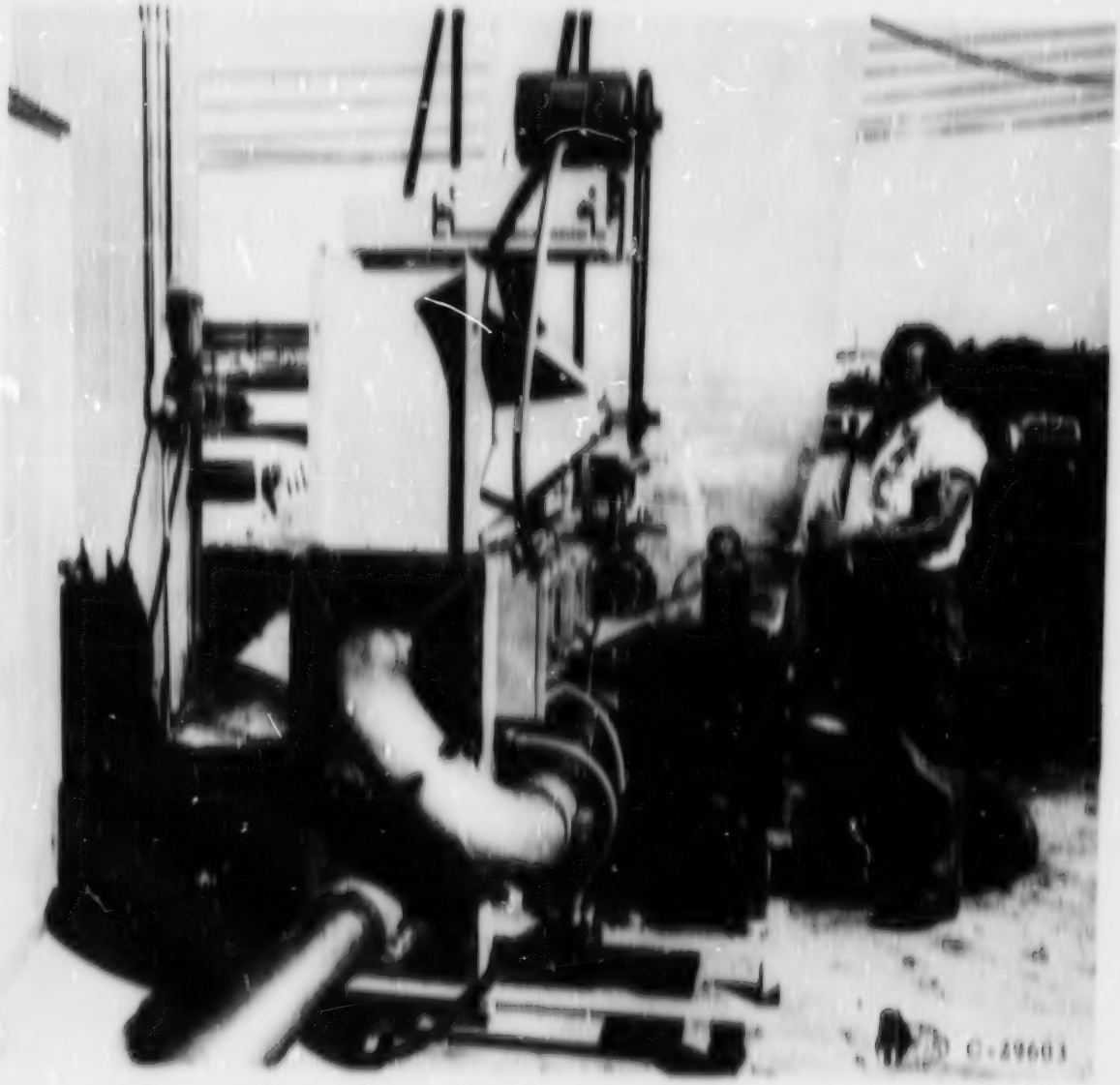

FIGURE 4. VARIABLE DILUTION SAMPLER - LEFT END VIEW

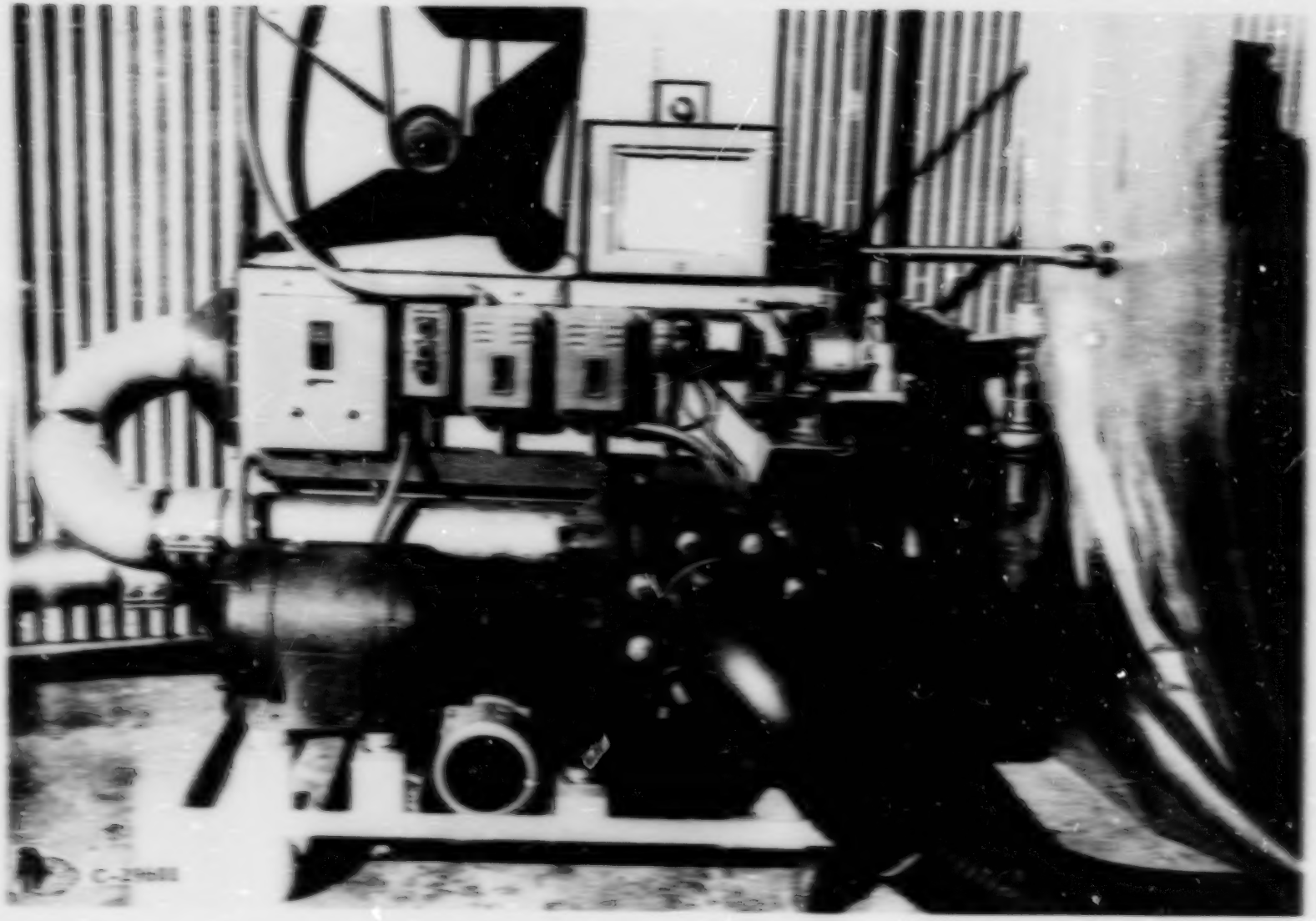

FIGURE 5. VARIABLE DILUTION SAMPLER - CLOSE FRONT VIEW

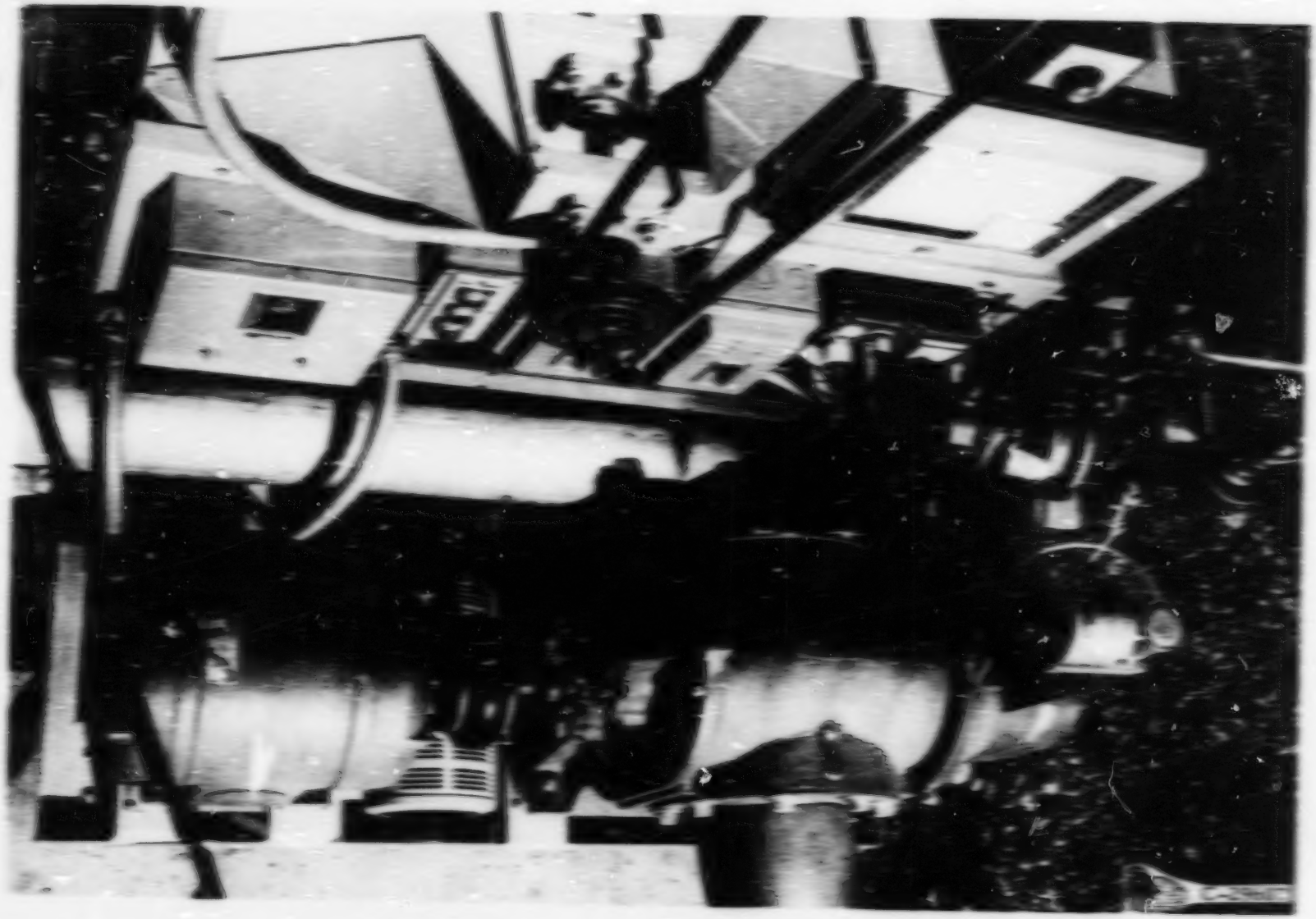

FIGURE 6. VARIABLE DILUTION SAMPLER - TOP VIEW

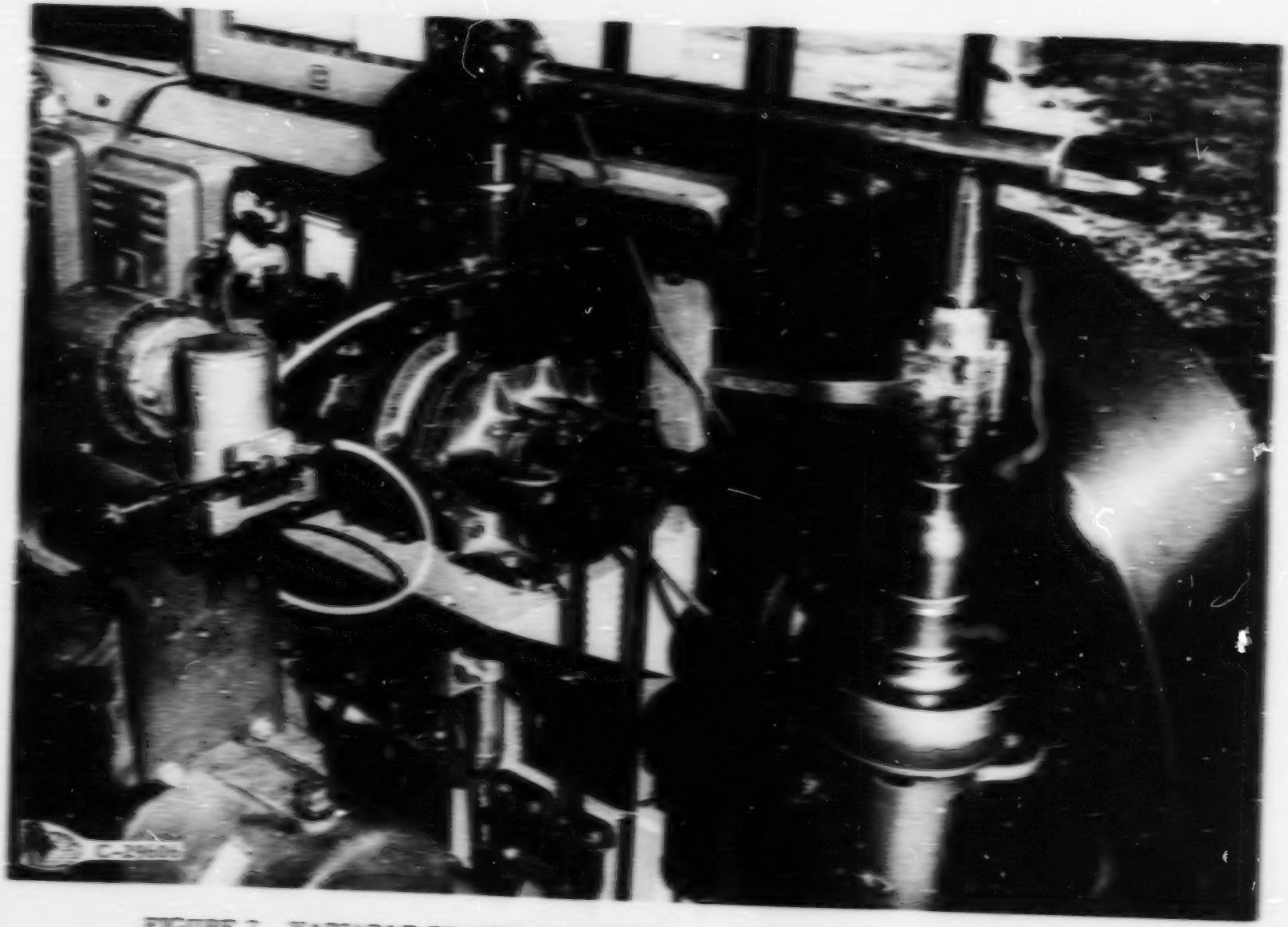

FIGURE 1. VARIABLE DILUTION SAMPLER - 1-IN. ID SAMPLE LINE. CLOSE-UP

FIGURE 6. VARIABLE DILUTION SAMPLER - CLOSE-UP OF SAMPLE PUMPS

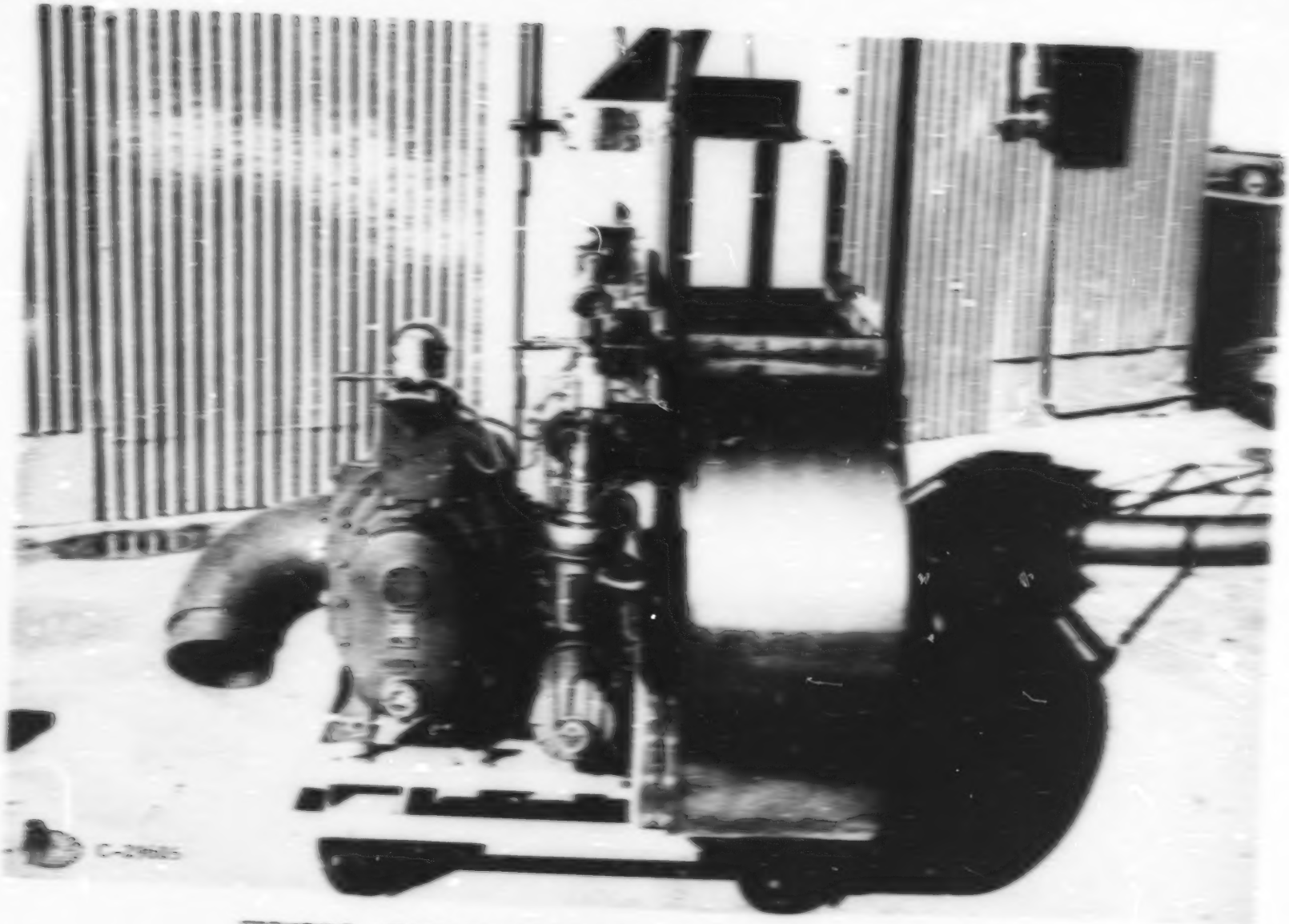

FIGURE 9. VARIABLE DILUTION SAMPLER - RIGHT END VIEW

knurled nut and Viton A O-ring assembly is employed to permit the sample probe, made from 1-in. stainless steel pipe, to be inserted and directed into the center of the straight section of 6-in. pipe. Not shown is the specially machined, stainless, isokinetic probe tip tightened on the end of the 1-in. probe. The threaded design feature permits replacement of the probe tip to permit isokinetic sampling, regardless of the system blower speed and dilute exhaust flow and velocity. Also shown in Figure 7 is the specially prepared sample pump. This pump was nickel plated inside and out and the shaft seals replaced with the Teflon® impregnated Garlock packing specified. The sample obtained via this pump was deposited in the 4 × 9-ft Tedlar bag illustrated in Figures 2, 4, and 5. As shown in Figure 7, the dilute exhaust gas sample enters the pump from the bottom and discharges vertically at the top through a three-way stainless steel valve and then into the sample bag. The speed and sample flow rate through the small gas sampling pump may be varied by replacement of the pump and motor pulley with units of varying numbers of teeth. A number of other pulleys, not shown, are supplied for this purpose.

A sixty-tooth gear and suitable magnetic pickup are shown mounted adjacent to the cog belt pulley and motor drive arrangement to permit measurement of the small pump speed. Once this speed was established, the sixty-tooth gear is replaced with a solid disc with a single hole drilled into the surface. The magnetic pickup now becomes a revolution counter such that the electronic counter may accumulate the total number of revolutions during a particular length of test cycle time. This system is routinely used in operation. Additional details of this part of the system may be seen in Figure 8, particularly the small diaphragm type Dynapump fitted with Viton A diaphragm and check valves. The Dynapump serves to transfer the diluted exhaust sample held in the large Tedlar bag to a small transfer bag for consequent analysis by standard instrument techniques. The gas is transferred via 1/4-in. stainless steel tubing connected to the large sample bag 24 in. above the sample inlet to the bag as shown in Figures 2 and 3.

The final photograph describing the variable dilution sampling system is Figure 9, the right-end view. Located inside of the 1-in. diameter stainless steel Kamlok bag quick-disconnect fitting is a thin stainless steel disc with a drilled opening. The use of this item will be discussed in the calibration section of this report. In operation, the Clements Cadillac suction pump, shown between the heat exchanger and system blower in Figure 9 and also shown below the aluminum two-way valve in Figure 7, is used to evacuate the large sample bag. Once this is accomplished, the three-way stainless steel valve, shown in Figures 7 and 8, directly above the sample pump is utilized to divert the sample

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stream into the large bag. The Leeds and Northrup Speedomax W single-pen temperature indicator-recorder is shown located over the heat exchanger in Figures 5, 8, and 9. Shown in Figure 5 is the six-position Thermo-Electric selector switch to permit any one of the following:

(1) Diluted gas temperature at inlet to heat exchanger,

(2) Diluted exhaust gas temperature at inlet to system blower,

(3) Outlet gas temperature from system blower,

(4) Diluted exhaust gas sample temperature at inlet to sample pump,

(5) Outlet sample gas temperature from sample pump,

(6) Ambient temperature near entrance to cooling air fan.

Close examination of the photographs will illustrate the location of these thermocouples, as well as static pressure tap locations for measurement of performance and for use in calibration.

C. Calibration

Calibration was the most important step in the preparation of the truck version of the PHS variable dilution sampler. The inherent simplicity in application and operation of this type of sampling system is predicated on a careful and accurate calibration. To analyse and compute emissions from samples obtained by this technique requires precise knowledge of the mass of exhaust handled by both the system blower and the sample pump. The temperature and pressure of the dilute exhaust, as well as the speed of rotation of both the blower and pump, affect the mass flow of dilute exhaust. These parameters must either be adequately controlled or measured for consequent use in computations.

As with the prototype automotive system, the gas pressure and pressure drop across the blower and pump and their speed of rotation were the parameters susceptible of control within acceptable limits. The temperature of the inlet gas to these units, although tempered by the heat exchanger, would not be adequately controlled to a given level, and therefore would have to be measured and used to correct for its effect on mass flow. Using guidelines and advice given by the designers and developers of the prototype, the calibration consisted of establishing speed and pressure drop parameters capable of control and which could be expected to be reasonably constant. The procedure used was to operate the entire system (high system blower speed) and measure the resulting pressure

drop first across the system blower and then across the sample pump while measuring the total throughput of air. The approach consisted of loading the system blower and drive motor to obtain the desired throughput of gas, yet maintain stable speed and blower operation for a given blower inlet temperature. The inside diameter of the mixing disc, located at the inlet to the heat exchanger, was varied to permit investigation of a variety of blower speeds and pressure drops. This variation of operating parameters resulted in an optimum pressure drop across the system blower of 16.4 in. of water at 80°F inlet temperature. Once the mixing disc ID of 4.873 in. was established, the same procedure was followed to establish the optimum set of operating conditions for the low speed configuration. This consisted of maintaining the same pressure drop determined for the high speed configuration of 16.4 in. H_2O by decreasing the ID of the inlet mixing disc to 3.146 inches.

Concurrent with establishing the pressure drop and inlet orifice inside diameter sizes for the low and high speed system blower capabilities, the sample pump was also investigated to establish a stable operating speed and load. As with the system blower, a small restriction in the form of a thin disc with a drilled hole was used to maintain a pressure drop conducive to stable pump operation and provide close to 4 cfm of sample. The procedure was to prepare the thin drilled disc for suitable operation of the sample pump during the high speed system configuration while measuring the sample flow rate and pressure drop. The resulting sample pump rpm was 760 rpm, with a pressure drop of 16.9 in. H_2O at 80°F inlet temperature. Using the same rpm and loading disc, the pressure drop across the sample pump was found to be 17.5 in. H_2O at 80°F inlet temperature when the system was operated at low speed.

To measure the flow rate of diluted exhaust gas, a 10-ft long ASME test section made from 6-in. Schedule 10 pipe was used. A thin plate orifice was mounted between flanges located 6-1/2 ft from the inlet of the test section. Flange tap type static pressure taps located 1 in. up stream and downstream of the nearer face of the 1/8-in. thick orifice plate were employed. This test section, along with the procedures used to calculate the flow rate through the orifice, was as specified in the Flowmeter Computation Handbook of the ASME Research Committee of Fluid Meters (Ref. 7). The test section orifice inside diameter was machined to produce the same constant pressure of 16.4 in. H_2O across the system blower with the mixing orifice, located at the inlet to the heat exchanger, removed. In effect, the ASME test section, connected to the inlet of the heat exchanger by means of the 15-ft long 6-in. diameter stainless steel flexible pipe, was designed to simulate the effect of the mixing orifice insofar as pressure drop, inlet pressure, and speed of the system blower was concerned. A Precision wet test meter capable of up to 100 cu ft/hr capacity was utilized to measure the flow rate of dilute exhaust sample handled by the sample pump. The outlet gas from this

pump was directed into the Tedlar sample bag for a 9-min period. The sample bag contents were then measured by a large wet test meter by counting the revolutions until the bag was evacuated. The small diaphragm pump, placed between the bag and meter, was used to transfer and evacuate the bag contents.

Using the operating speeds and pressure drops determined during the exploratory studies and the measurement methods previously described, calibration of the system was conducted. Following the procedure used in the automotive prototype, curves were established relating flow of the system blower or sample pump to its inlet temperature. For the truck version the inlet temperature to the system blower and to the sample pump were basially identical, within 1°F of one another. Listed in Table I are the results of the flow calibration of the truck version variable dilution sampling system. The low speed results are listed first, with the system blower operated at 1150 rpm, with the 3.146-in. ID inlet mixing orifice and the 0.490-in. ID isokinetic sample probe installed. The high speed results are then listed for the system blower operated at 1700 rpm with the 4.873-in. ID mixing orifice and 0.402-in. isokinetic probe tip employed. The inlet temperature into the blower-pump (essentially the same under all conditions investigated) was varied by heating the air at the inlet to the ASME test section. Calibration data were first obtained with an oxy-acetylene welding torch heat source and then repeated using actual vehicle exhaust. The values shown are actual flows in cfm at pressure and temperature conditions as measured at the inlet to the blower pump. These actual flows for both the system blower and sample pump were then added to obtain the total sample system throughput. As with the automotive calibration, the actual cfm were corrected to standard flowing conditions defined as 68°F and 14.7 psia.

Shown in Figures 10 and 11 are plots of the actual cfm of gas handled by the system blower and sample pump over an inlet temperature range of 60° to 110°F for low speed, 1150-rpm system operation. When these two flows are combined and computed in terms of standard conditions, the result is a linear decrease in flow scfm, with an increase in flowing temperature (pressure constant) per Figure 12. With the flow in standard or scfm terms, the mass flow of total exhaust and diluent can be obtained by simply measuring the inlet temperature to the blower or pump. Knowing the inlet temperature, Figure 13 may be used as the system mass flow calibration curve in computing mass emissions. A description of the computation procedure is included in a later section. Figures 14, 15, and 16 are plots of the flow data versus temperature obtained during the high speed system calibration. Figures 14 and 15 show the linear relationship of actual flow, in terms of the inlet pressure and temperature to the system blower and sample pump. Figure 15 shows the combined total flow rate, in terms of scfm at 14.7 psia and 68°F, for the high speed configuration. As with Figure 12, this curve is the calibration curve used in computing mass flow and mass emissions.

TABLE 1. FLOW CALIBRATION OF TRUCK VERSION OF PHS VARIABLE DILUTION SAMPLING SYSTEM

Measurement Method

System Blower: 10-ft long, 6-in. diameter ASME test section thin plate orifice located before the 6-in. diameter flex pipe. Mixing baffle removed.

Sample Pump: Precision wet test meter and diaphragm pump exhausting contents from sample bag.

System Blower Speed, rpm	Temperature Inlet to Blower Pump, °F	System Blower* Flow, cfm	Sample Pump* Flow, cfm	Total Sampler* Flow, cfm	Total Sampler† Flow, scfm
1150 (low)	60	641.32	4.98	646	660
	70	644.92	4.08	649	65[illegible]
	80	650.86	4.14	655	644
	90	659.79	4.21	664	634
	100	669.71	4.29	674	621
	110	678.60	4.40	683	[illegible]
1700 (high)	60	968.86	4.14	973	995
	70	974.83	4.17	979	978
	80	989.72	4.28	994	975
	90	1005.65	4.35	1310	970
	100	1020.61	4.39	1025	961
	110	1035.54	4.46	1040	944

*Cfm is actual cfm for the blower-pump actual inlet pressure and temperature conditions.
†Scfm is cfm corrected to standard conditions of 68°F and 14.7 psia.

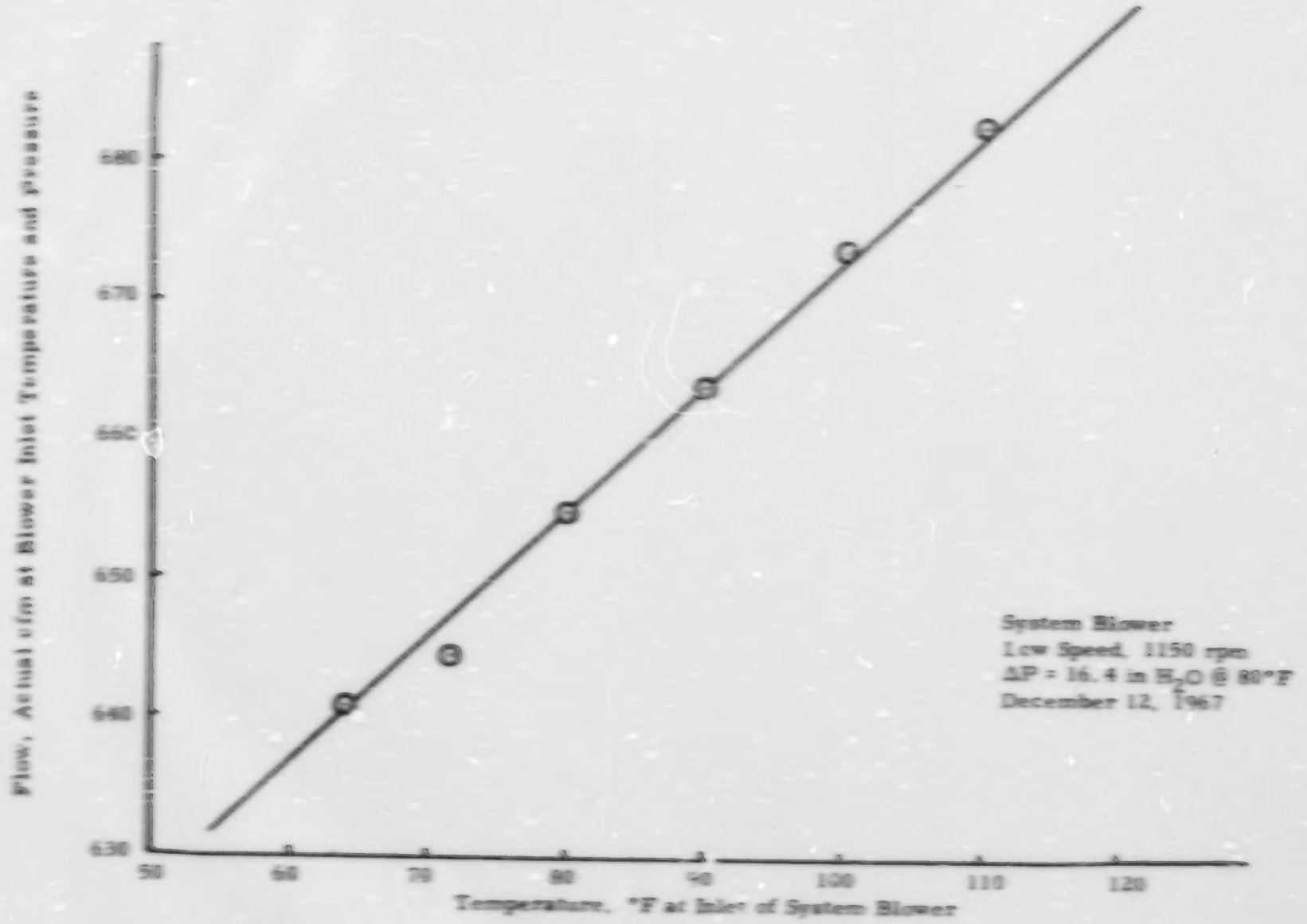

FIGURE 16. FLOW CALIBRATION OF SYSTEM BLOWER
During Low Speed, 1150-rpm, Operation of System Blower

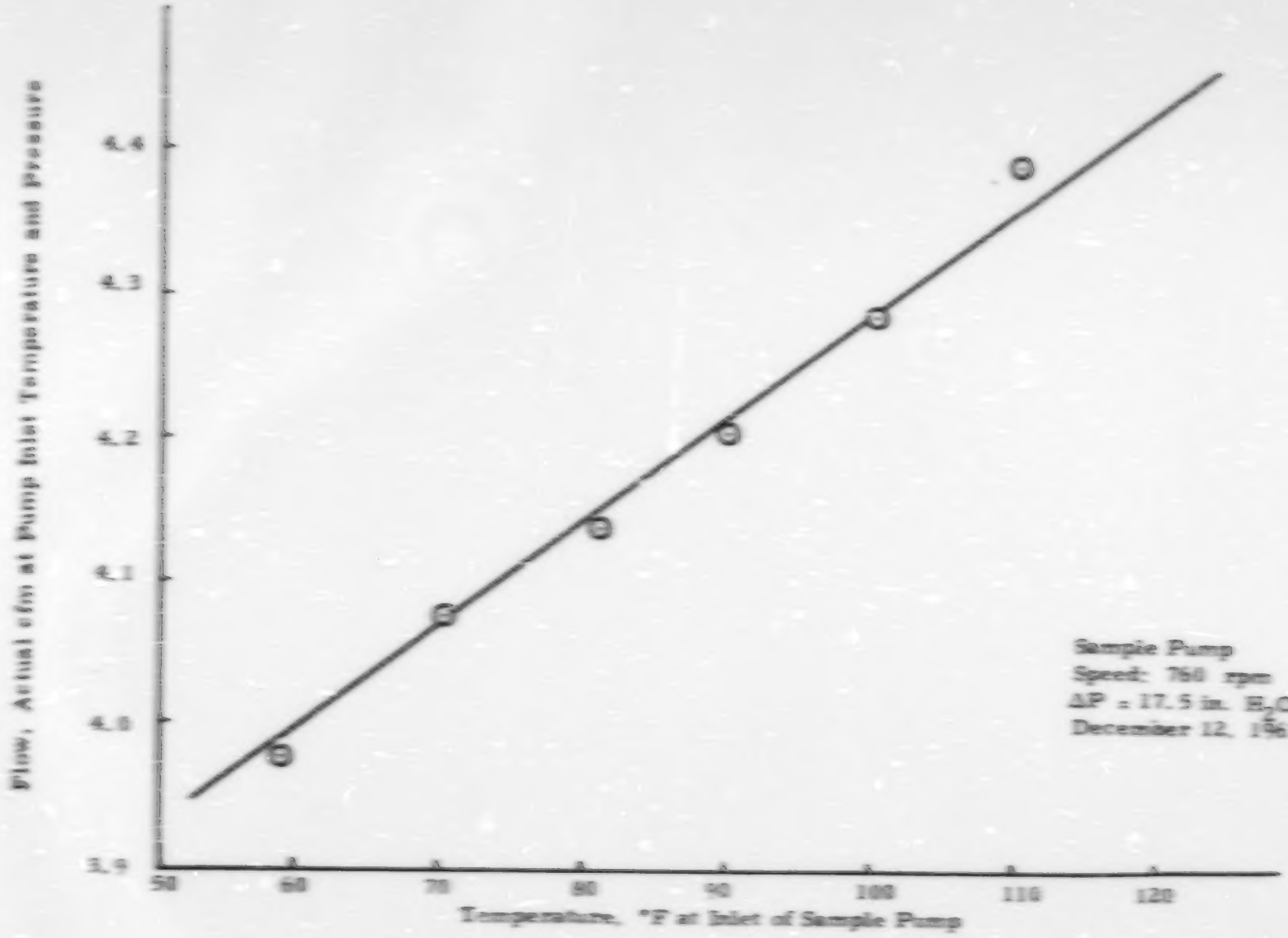

FIGURE 11. SAMPLE FLOW CALIBRATION OF SAMPLE PUMP
During Low Speed, 1150-rpm, Operation of System Blower

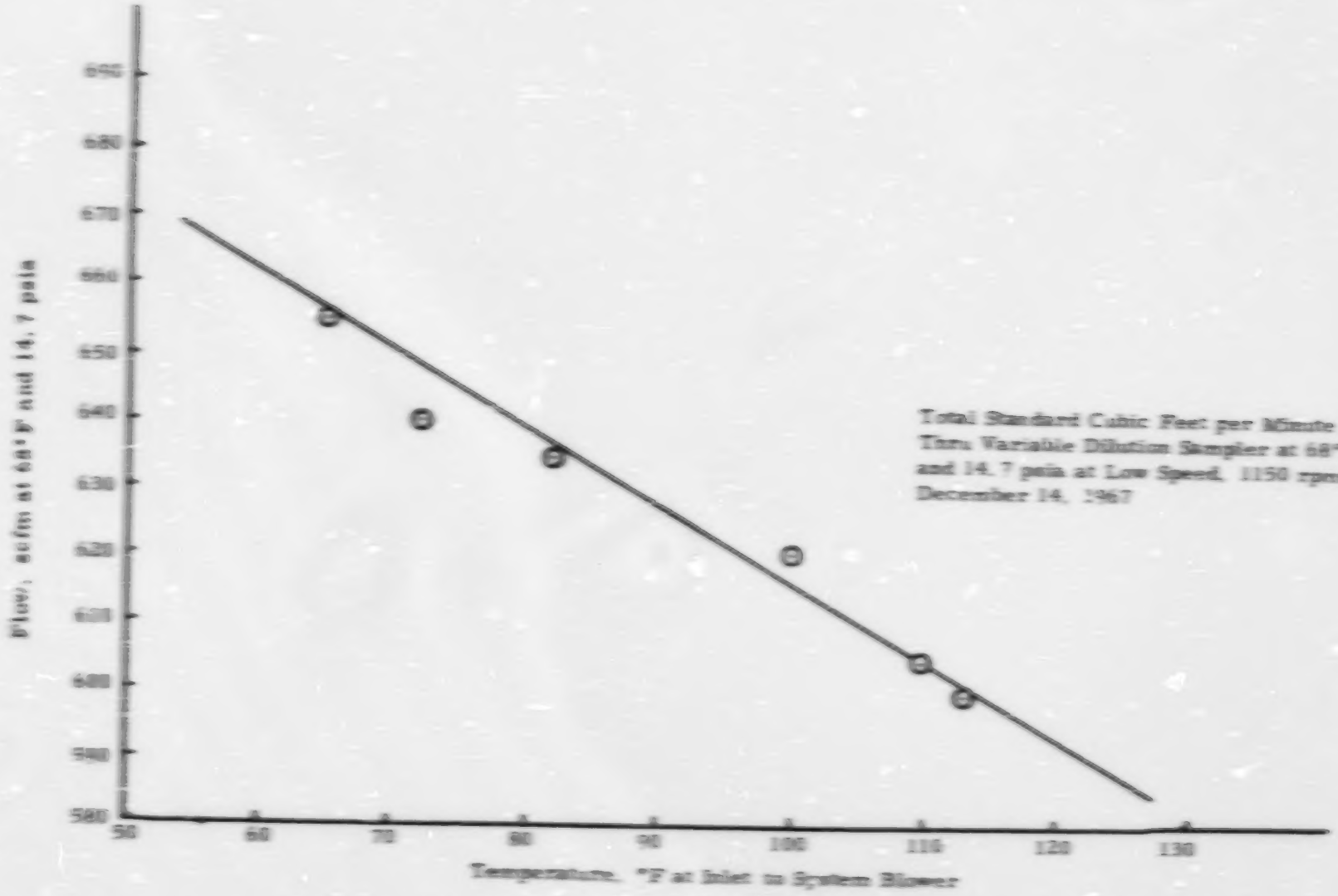

FIGURE 12. STANDARD FLOW CALIBRATION OF SYSTEM BLOWER
(Low Speed, 1150-rpm, Configuration)

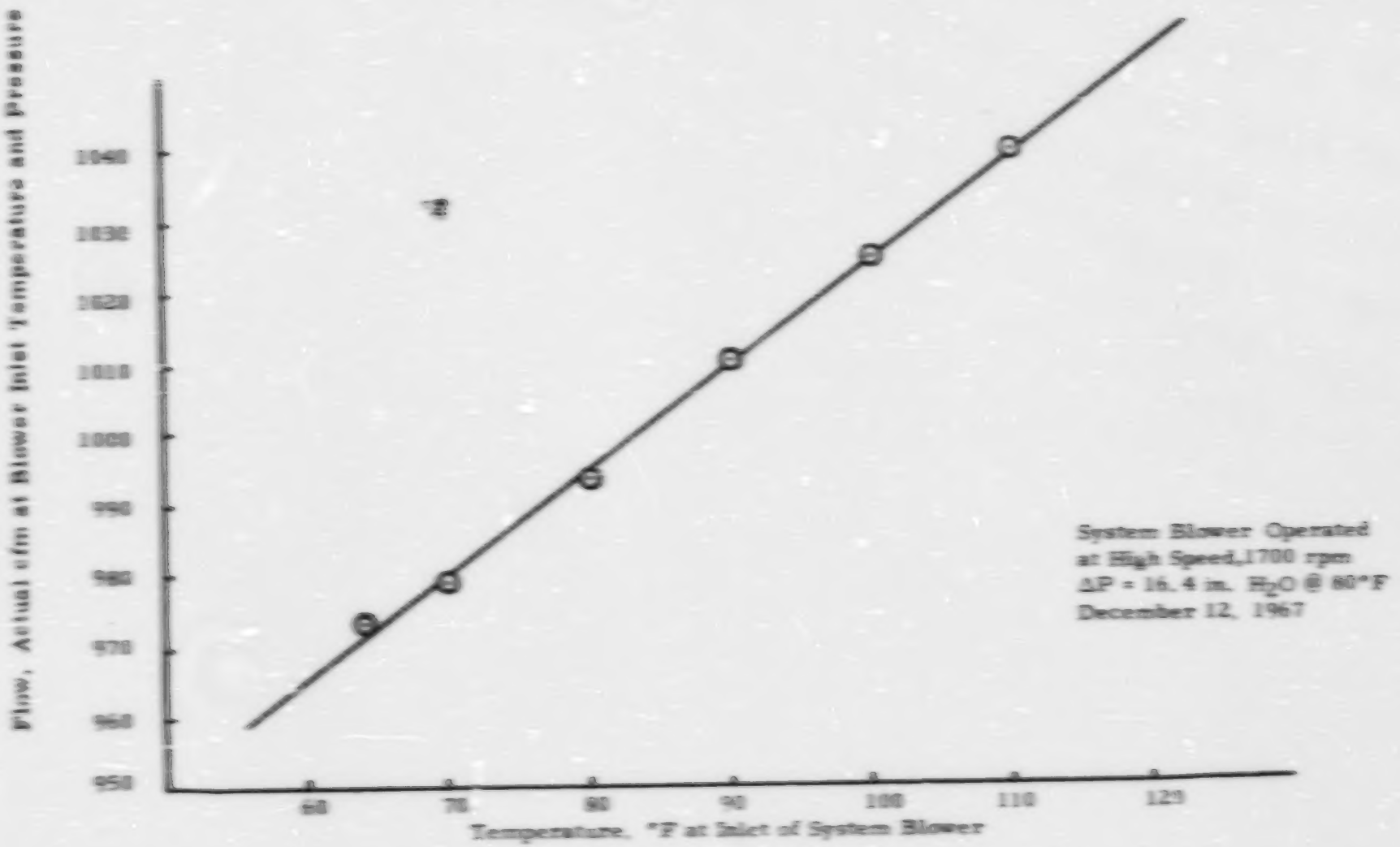

FIGURE 13. FLOW CALIBRATION OF SYSTEM BLOWER
During High Speed, 1700-rpm, Operation of System Blower

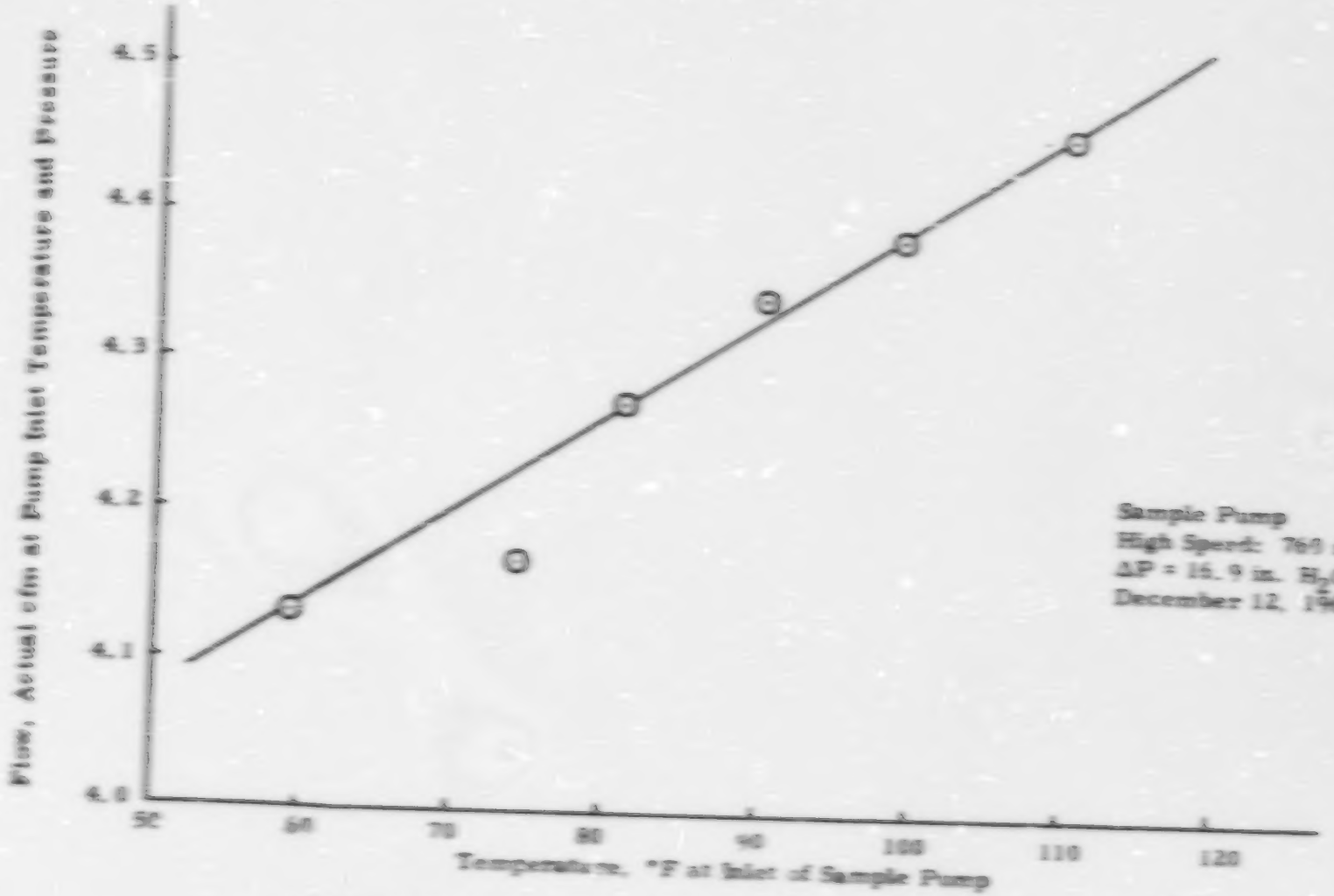

FIGURE 14. SAMPLE FLOW CALIBRATION OF SAMPLE PUMP
During High Speed, 1700-rpm, Operation of System Blower

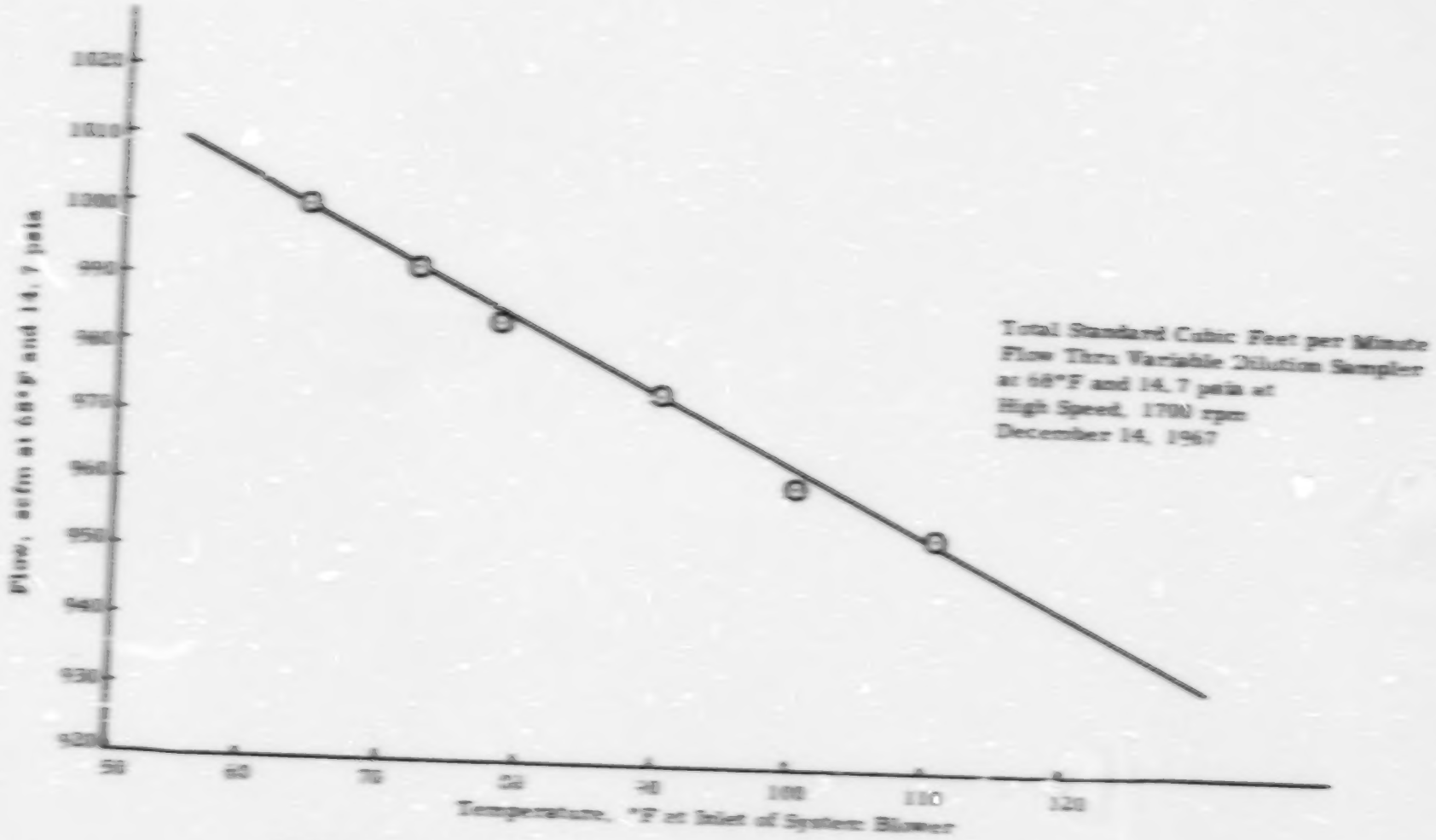

FIGURE 15. STANDARD FLOW CALIBRATION OF SYSTEM BLOWER
(High Speed, 1700-rpm, Configuration)

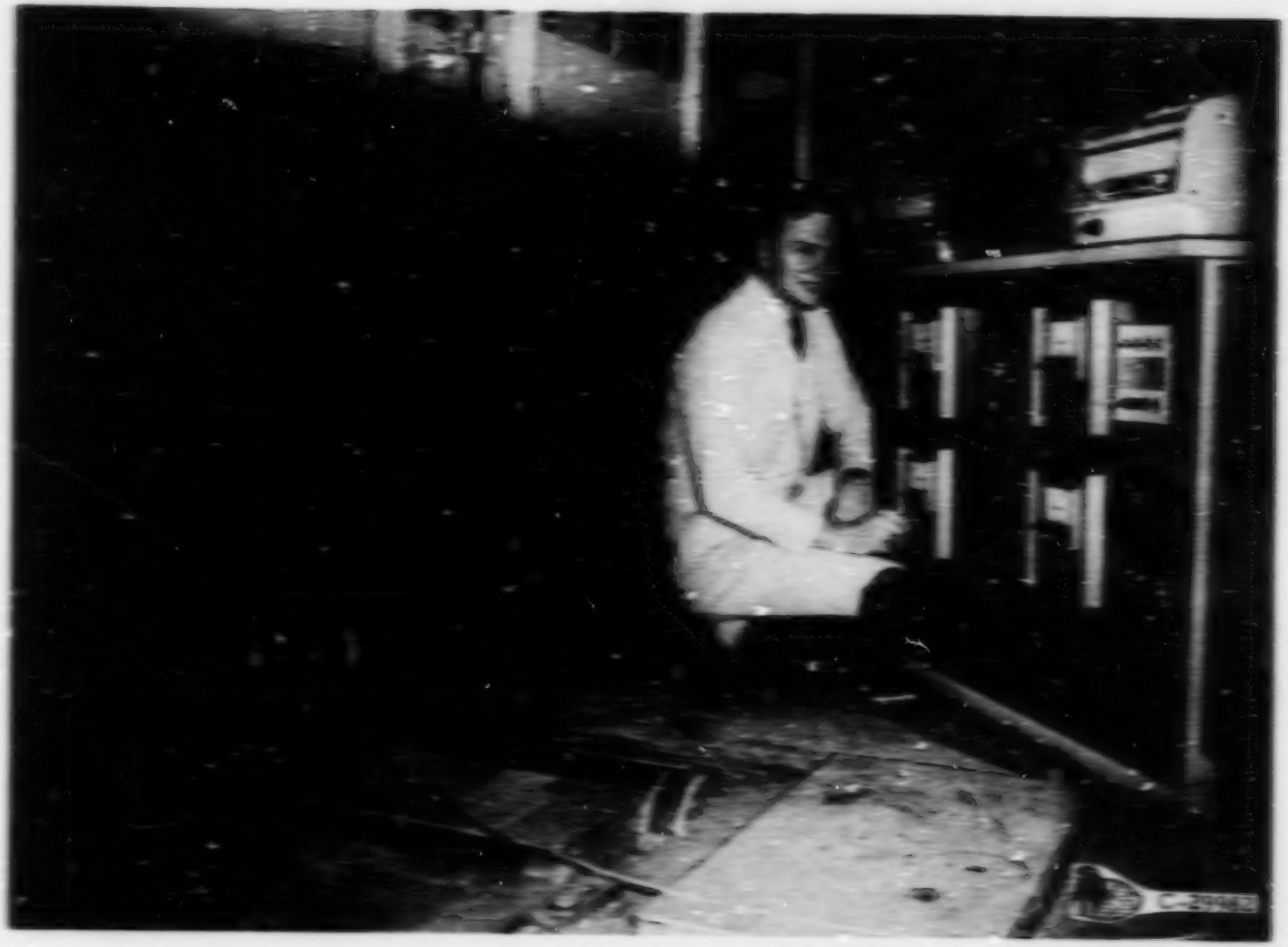

FIGURE 16. VARIABLE DILUTION SAMPLER INTAKE PIPE WITHOUT CONE

While acquiring the calibration data, a brief study was made as to the effect of power supply variations in line voltage on the resulting system blower speed and pressure drop. Making use of the three-phase powerstat to vary the voltage applied to the two-speed motor drive for the system blower, a minor variation in pressure drop and small variation in blower speed were obtained. The following pressure drops and blower speeds were measured with the mixing orifice installed.

System Blower Motor Voltage, volts	Low Speed System Blower		High Speed System Blower	
	ΔP, in H_2O	Speed, rpm	ΔP, in H_2O	Speed, rpm
200	16.4	1135	16.2	1672
210	16.45	1141	16.3	1685
220	16.50	1149	16.4	1697
230	16.60	1154	16.5	1705

As indicated above, the variation in line voltage had little effect on the low speed system performance but had a significant effect on the speed of rotation, and cfm, throughput when the motor was operated at high speed. Since the powerstat permits manual adjustment of the input voltage regardless of voltage supply, this variable may be easily controlled and maintained at 220 volts.

After operating the variable dilution sampler in a correlation study, it was found that the approximate 950 total scfm flow rate of the variable dilution sampler affected the exhaust emission when the flexible intake pipe of the sampler was placed over the exhaust pipe of the vehicle. Placing the sampler intake pipe as shown in Figure 16 created a partial vacuum in the vehicle exhaust system. Using a U-tube manometer connected to a static pressure tap between the muffler and engine of the truck, it was found under idle and other closed throttle conditions that up to 4 in. H_2O less pressure than normal was induced by the action of the high entrainment of diluent. A design change of attaching a cone on the entrance of the stainless steel flexible pipe reduced the high entrance velocity and eliminated the partial vacuum in the exhaust system created by the system blower. An 18-in. long cone, increasing the inlet diameter from 6 to 12 in. (113 instead of 18.8 sq in.), was effective in reducing the inlet velocity from 7280 to 1210 ft/min during high speed operation. This cone, shown in Figure 17, appears to have no effect on engine-vehicle operation and is suggested for addition to the truck version of the PHS sampler.

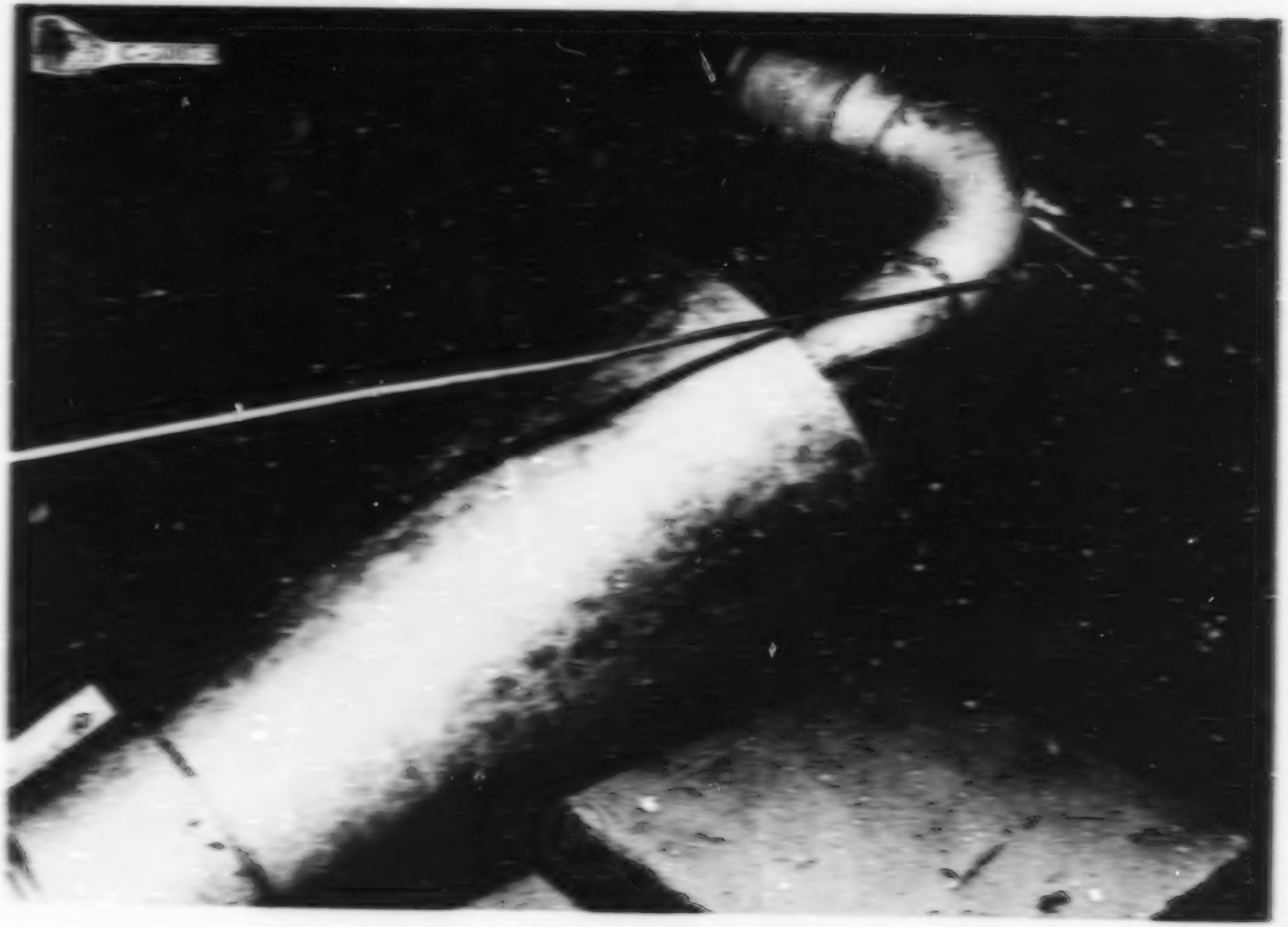

FIGURE 17. EXHAUST INLET CONE FOR USE WITH TRUCK VERSION PBS VARIABLE DILUTION SAMPLER

D Sampling, Analysis and Computation Procedure

A tentative sampling procedure developed for the two-speed truck version of the variable dilution sampling system is described in Table 2. Following this procedure stepwise will result in the Tedlar sample bag holding approximately 4 cu ft of diluted sample for every minute of operation. Once the sample procedure has been conducted, about 2 to 3 cu ft of the diluted and bagged exhaust is transferred to a small Tedlar transfer bag. This more manageable quantity of exhaust is then carried into the analytical laboratory for measurement of CO, CO_2, unburned hydrocarbons, oxides of nitrogen. The analysis cart incorporating suitably spanned, low range Beckman 315 nondispersive infrared analyzers for CO, CO_2, and unburned hydrocarbons is shown in Figure 18. Also shown is the Beckman 109 flame ionization detector instrument used to measure total unburned hydrocarbons as ppm C. Not shown is a Beckman polarograph instrument for oxygen determination. A modified Saltzman syringe technique was employed to measure total NO_x as ppm NO_2. The NO_x, prevalent in the engine exhaust at time of sampling and analysis, is purposely oxidized to its more stable state, NO_2, and the concentration read colorimetrically as ppm NO_2.

After the analysis of the transfer bag contents is complete and the meter readings recorded on the data sheet shown as Table 3, the computations of the mass emissions may be accomplished. Referring to Table 3, the following data reduction system, identical to that used with the automotive system and in accord with Reference 3, may be used to obtain the desired end result, namely mass emissions on a pound/mile or gram/mile basis:

(1) Record the distance traveled, and the overall average integrated temperature of the sample from the recorder. (Use the sample pump inlet temperature reading.)

(2) Record the total sampling time ("T") and the number of cycles sampled ("A").

(3) Go to calibration curve of standard cubic feet flowed versus sample temperature, Figures 14 or 15, and record the scfm flowed ("V").

(4) Convert revolutions of dynamometer rolls to miles per cycle ("D").

(5) Compute SCF/mile (VT/DA).

(6) Read concentrations of HC, CO, CO_2, NO_x, and O_2 and record.

TABLE 2. TENTATIVE OPERATING PROCEDURE FOR PHS VARIABLE DILUTION SAMPLING SYSTEM

General:

To obtain a bag sample of vehicle exhaust for emissions analysis, the high speed 4.873 in. ID inlet orifice and 0.402 in. ID isokinetic sample probe must be used with the high speed 1700-rpm system blower speed. The low speed, 3.146-in. ID inlet orifice and 0.49-in. ID isokinetic sample probe must be used with the low speed 1150-rpm system blower speed.

Procedure:

(1) Set powerstat to give 220 volts and start cooling fan, "high" or "low" system blower and sample pump. Adjust powerstat to exactly 220 volts on voltmeter to give 1700 or 1150 rpm. Note: Do not change from high to low speed system blower without permitting speed to decrease to less than 1150 rpm.

(2) Turn "on" Cadillac suction fan to evacuate sampling bag. The three-way valve closed to sample pump and sample pump vented to atmosphere.

(3) After sample bag is evacuated, simultaneously close two-way aluminum valve and move three-way valve to permit sample to enter bag. This movement will start the electronic counter which has been zeroed. Normally, this step will coincide with the start of the chassis dynamometer cycle.

(4) At end of chassis dynamometer cycle, move three-way valve to permit sample to be vented. Do not move two-way aluminum valve.

(5) Record applicable items on variable dilution sampler data sheet.

(6) Using the Dynapump transfer system, transfer from large sample bag into transfer bag. Assist gas mixing in large bag by shaking. Permit the first 10 to 15 sec of transfer gas to be vented before "plugging-in" the transfer bag.

(7) Always leave large bag evacuated or partially filled with laboratory air when unit is to be shut down.

(8) Turn off all instruments, blowers/motors and turn powerstat to "0" when system is to be shut down overnight.

FIGURE 10. BAG SAMPLES OF VEHICLE EXHAUST ANALYZED BY FLAME IONIZATION AND NONDISPERSIVE INFRARED METHODS

TABLE 3. DATA SHEET FOR VARIABLE DILUTION SAMPLING SYSTEM

Bar _____ in Hg
Corr _____ in Hg
Wet _____ °F
Dry _____ °F
Date _____ Engine Make _____ Project _____
Run No. _____ Cyl/Disp ____/____ Tire Size _____
Vehicle Year/Make _____/_____ Trans. No. _____ Odometer _____
Type Vehicle _____ Axle Ratio _____ No. of Axles _____
Cycle Description _____
Time of Day _____ Blower Speed _____ High ____ Low
Total Distance Traveled _____ rev. of 8-3/8-in. OD dyno rolls

Integrated Overall Average Gas Temperature at Inlet to Sample Pump _____ °F

T: Total Sampling Time _____ min

A: Number of Cycles Sampled _____

Calculate:

V: Total SCFM from Applicable Calibration Curve _____ SCFM

D: Miles Traveled per Cycle, $\frac{\text{Dyno Rev.} \times 4.15 \times 10^{-4}}{\text{Number of Cycles Operated}}$

$$= \frac{(\quad) \times 4.15 \times 10^{-4}}{(\quad)} = ____ \frac{\text{miles}}{\text{cycle}}$$

Standard Cubic Feet per Mile:

$$\text{SCF/MILE} = \frac{VT}{DA} = \frac{(\quad)(\quad)}{(\quad)(\quad)} = ____ \text{SCF/MILE}$$

Meter Reading	Concentration		SCF/Mile	%/100	Lb Mol Wt 385.3	Lb/Mile
	HC/Infrared	ppmc			0.03597	
	HC/FIA	ppmc			0.03597	
	CO	%			0.07269	
	CO_2	%			0.11422	
	NO_x	ppm			0.11940	
	O	%				

NO_x Syringe No. 1 _____ No. 2 _____ Bag No. _____

(7) Convert concentration reading to common basis as %/100.

(8) Multiply (SCF/mile) × (%/100) × (lb mol wt) conversion factor to obtain lb/mile and record. Conversion factor is listed in the Appendix per Reference 1.

The above sampling, analysis, and computational procedures, associated with the variable dilution sampling system, are the simplest to use of all known bag or continuous systems. This method is easy and quick to use and appears highly reliable based on data obtained to date. The run-to-run repeatability obtained and inherent via this system seems to justify the system concept and design.

E. Limited Typical Results

To complete this discussion of the truck size variable dilution sampler, limited, preliminary results are presented in Table 4. For comparison purposes, simultaneous variable dilution and proportional samples were obtained. The Pace proportional sampling system procures an exhaust sample proportional to the airflow rate through the carburetor. The emissions data for Table 4 were obtained using an experimental twelve-mode cyclic test procedure at level road load and uphill road load for the Class IV 1966 International Harvester V-8 truck. A ten-mode cycle at level road load experimental test procedure was employed with a Class III, 1965 Chevrolet, six-cylinder truck. Comparing the average values (minimum of four runs involved for each sampler comparison series) indicates that unburned hydrocarbons by both methods are always greater for the variable dilution sampler regardless of vehicle or cycle load. NO_x values were also higher for the Class IV experiments at level road load, about the same for the Class IV uphill road load condition, and less for the Class III runs. CO, on a pound/mile basis, showed excellent agreement throughout this series of runs, regardless of vehicle dynamometer cycle. CO_2, like unburned hydrocarbons, was always greater for the variable dilution method.

To gain a better understanding of the system's temperature characteristic, various temperatures were recorded during a typical experimental ten-mode Class III chassis dynamometer cycle at level road load. This cycle was run four consecutive times in a total time of 7 min. Figures 19 and 20 show the heat exchanger inlet and outlet diluted exhaust temperatures during the four cycles and indicate the effectiveness of this item as a "heat sink." The dilute exhaust temperatures at the inlet and outlet of the sample pump are shown in Figures 21 and 22. The effect of the sample pump is to smooth out the sample temperature without a noticeable addition of heat by the pump.

TABLE 4. COMPARISON OF PACE PROPORTIONAL SAMPLER WITH VARIABLE DILUTION SAMPLER EMISSION RESULTS

Vehicle	Cycle	Sampler		NDIR UBHC, lb/mi	FIA UBHC, lb/mi	NO_x, lb/mi	CO, lb/mi	CO_2, lb/mi
Class IV 1966 IHC 345 V-8	*	Pace Proport.	Max	0.0244	0.0498	0.0131	0.412	1.890
			Min	0.0229	0.0483	0.0125	0.426	1.814
			Avg	0.0236	0.0489	0.0127	0.421	1.844
		Variable Dilution	Max	0.0252	0.0541	0.0201	0.436	2.095
			Min	0.0245	0.0479	0.0161	0.406	1.890
			Avg	0.0248	0.0517	0.0172	0.438	1.980
Class IV 1966 IHC 345 V-8	†	Pace Proport.	Max	0.0250	0.0552	0.0216	0.418	2.57
			Min	0.0197	0.0434	0.0161	0.367	2.07
			Avg	0.0214	0.0478	0.0184	0.393	2.295
		Variable Dilution	Max	0.0247	0.0542	0.0208	0.427	2.575
			Min	0.0240	0.0520	0.0161	0.373	2.370
			Avg	0.0242	0.0532	0.0188	0.397	2.49
Class III 1965 Chev 292 cu in.	‡	Pace Proport.	Max	0.0270	0.0505	0.0286	0.498	3.075
			Min	0.0241	0.0434	0.0218	0.428	1.90
			Avg	0.026	0.0482	0.0238	0.457	1.96
		Variable Dilution	Max	0.0310	0.0657	0.0232	0.496	2.197
			Min	0.0260	0.0635	0.0176	0.439	2.055
			Avg	0.0288	0.0648	0.0205	0.466	2.121

*PHS twelve-mode Experimental Class IV Cycle at Level Road Load.
†PHS twelve-mode Experimental Class IV Cycle at Moderate Uphill Road Load.
‡PHS ten-mode Experimental Class III Cycle at Level Road Load.

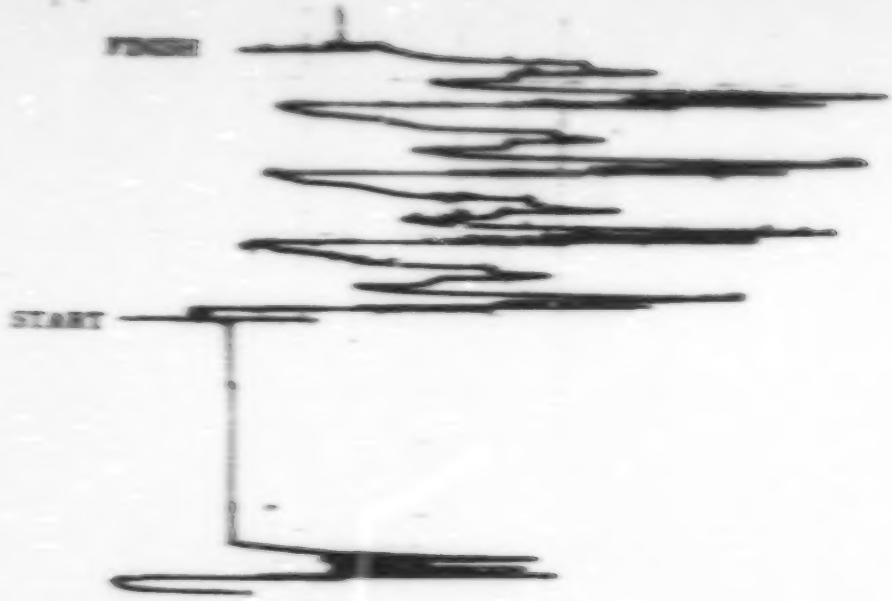

Chart Speed:
15 in/hr

FIGURE 19. GAS TEMPERATURE AT INLET TO HEAT EXCHANGER
1965 Chevrolet Van - 292 - Six Cylinder - January 9, 1968

Chart Speed:
15 in/hr

FIGURE 28. TEMPERATURE OF GAS AT EXIT FROM HEAT EXCHANGER AND AT INLET TO SYSTEM BLOWER
1965 Chevrolet Van - 292 - Six Cylinder - January 9, 1968

FIGURE 21. TEMPERATURE OF GAS AT INLET TO SAMPLE PUMP
1963 Chevrolet Van - 292 - Six Cylinder - January 9, 1968

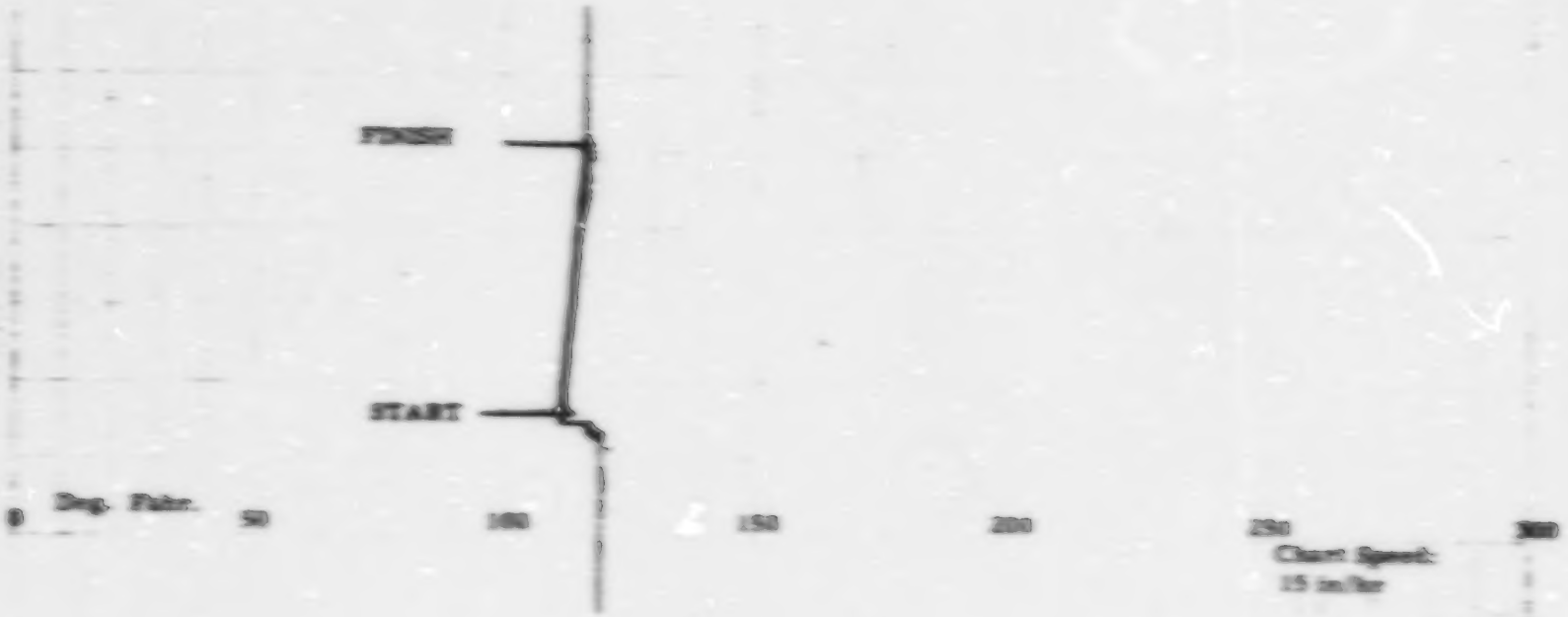

FIGURE 22. TEMPERATURE OF GAS AT EXIT OF SAMPLE PUMP
1965 Chevrolet Van - 292 - Six Cylinder - January 9, 1968

III. SUMMARY

Using the automotive prototype variable dilution sampler as a guide, a new version of this sampling system for use with trucks above 10,000-lb GVW has been prepared. The major change with the truck version was the capability of handling a threefold increase in exhaust and diluent airflow. This change necessitated a larger system blower and motor, as well as changes to the stainless steel air-to-air heat exchanger. The heat exchanger changes involved larger size tubes through which the exhaust and diluent air pass, as well as a substantially increased cooling air fan. In preparing the truck version, other design features were incorporated to improve and broaden the capability of the system. One major feature was the use of a two-speed motor to drive the system blower, and thereby provide approximately twice the air handling capability of the automotive prototype for use with trucks of the medium size category. Control features to maintain stable, repeatable, sampling system operation included a powerstat for control of motor and rotary pump speed, continuous temperature record, and provision for measuring system blower and sample pump speed, and sample pump revolutions.

A successful calibration of the two-speed truck version variable dilution sampler was accomplished and suitable operating procedures, analysis, and computation techniques prepared. During the calibration step, it became evident that an additional item, an inlet cone, was necessary to reduce the exhaust and diluent air velocity at the inlet to the 6-in. flexible exhaust pipe. This additional component was capable of handling the total exhaust of the vehicle, plus the diluent air without noticeably affecting the operation of the vehicle engine or its emissions at both system design speeds. A limited comparison of the truck version of the variable dilution sampler with the proportional sampling system (Pace sampler) was also conducted. These limited results, obtained with a Class III and Class IV gasoline powered truck operated under a level road load and uphill road load cyclic test procedure, indicated higher overall mass emissions on a pound/mile basis with the variable dilution system versus the proportional system. Repeatability and reliability of the variable dilution system have been found to be noticeably better than with other vehicle exhaust sampling procedures and systems available.

REFERENCES

1. Louis C. Broering, Jr., William J. Werner, Andrew H. Ross, Jr., "Automotive Mass Emission Analysis by a Variable Dilution Technique," Presented at the APCA Annual Meeting, June 1967.

2. ASME, Flowmeter Computation Handbook, Prepared by the ASME Research Committee on Fluid Meters, The American Society of Mechanical Engineers, 1961.

3. Correspondence, Ralph Stahman, NCAPC, Cincinnati, Ohio, to Karl Springer, SwRI, dated November 24, 1967.

APPENDIX

CONVERSION FACTOR TO GET LB/MILE BASIS

(22.41 L/gram-mole)(ft^3/28.32L)(453.6 gram-mole/lb mole)(528/492) =

$$\frac{(22.41)(453.6)(528)}{(28.32)(492)} = 385.2 \quad \text{SCF (68°F)/lb mole}$$

TO GET LB MASS/MILE FROM CONCENTRATION

[Total SCF (68°F)/mile flowed]($\% \times 10^{-2}$ concentration)

$$\left(\frac{\text{mol wt (lb mass/lb mole)}}{385.2 \text{ SCF (68°F)/lb mole}}\right) = \text{lb/mile}$$

Note: The above per correspondence from Mr. Ralph Stahman, NCAPC, Cincinnati, to Karl Springer, SwRI, dated November 24, 1967.